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Absorption and Photoluminescence Investigations of Excitonic Transitions in Compressively Strained InGaAs/InGaAlAs Multiple Quantum Wells

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Introduction

Excitons in quantum wells (QWs) have received much attention in recent years. This is because investigations of excitonic transitions provide valuable information for better understanding of QW physics, and there exists a large potential for utilizing enhanced excitonic effects in QWs for practical device applications. The properties of excitons in QWs depend greatly on the details of QW structure such as well composition and thickness, and such dependence needs to be thoroughly understood for any practical applications of excitons. In this paper, we present the results of our investigations in which excitonic transitions in compressively strained InGaAs multiple QWs on InP are studied by absorption and photoluminescence (PL) measurements. Specifically, quantitative exciton parameters such as transition energies, exciton binding energies and radii are estimated from absorption measurements. Comparison is made between strained and lattice-matched QWs. From PL measurements, luminescence characteristics are qualitatively analyzed as a function of well thickness and temperature.

Experiments

The strained multiple QWs investigated were grown by solid-source molecular beam epitaxy (MBE) on semi-insulating (001) InP wafers. Utilizing two separate gallium cells, wells and barriers of different compositions were grown without any growth interruption. Details of MBE growth can be found elsewhere [1]. Three samples with four strained multiple QWs were grown under the same growth condition on the same day. As can be seen in Figure 1, the samples have the identical p-i-n structure except for the different well thicknesses of 2.5, 5.0 and 7.5 nm for Sample A, B, and C, respectively. P-i-n structure was used because it is the device structure for modulator and laser diode applications, and the built-in field in such structure was expected to enhance the signal levels for PL and photomodulated transmission measurements. The layer composition and thickness were accurately determined from double-crystal x-ray diffraction measurements and simulations. The well composition is $In_{0.652}Ga_{0.348}As$, corresponding to 0.83 % compressive strain. All the strained layers are believed free of major strain relaxations as evidenced by dislocation-free surface morphology, sharp satellite peaks observed in the double-crystal x-ray measurements, and narrow and strong low-temperature PL peaks [1].

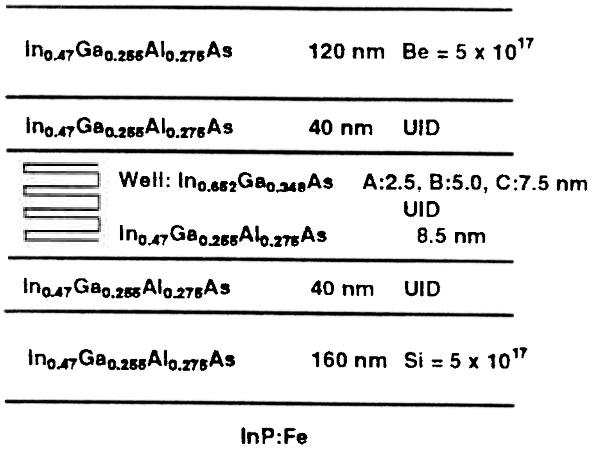

Figure 1: Layer Structures for Strained MQWs

Transmission measurements were performed at room temperature (RT) utilizing a tungsten lamp, a 0.275 m single-path monochrometer, a PbS detector, and a lock-in amplifier. Since InP substrates are transparent to the wavelength of interest, a simple,

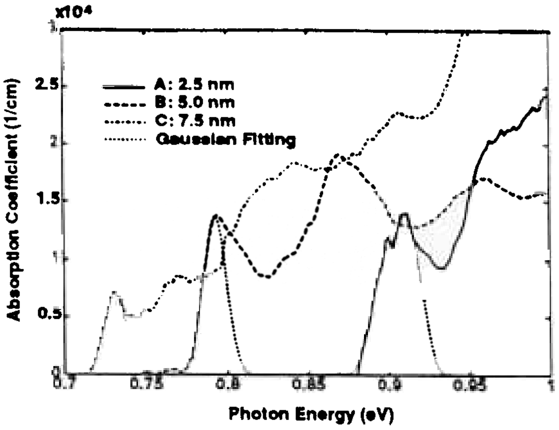

Figure 2: Absorption Spectra

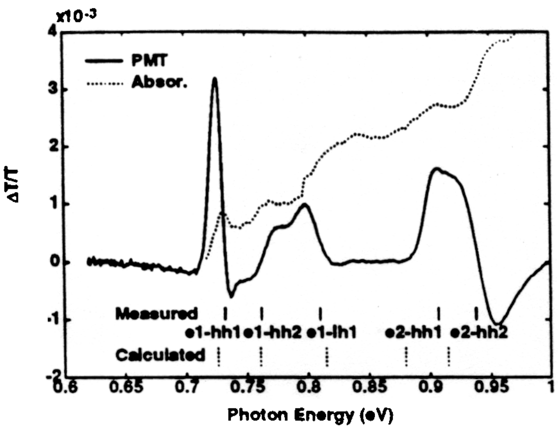

Figure 3: Absorption and PMT Spectra

normal incidence transmission geometry was used. The results from the measurement were corrected for any extrinsic effects by subtracting the background signals obtained in the same measurement configuration without a sample. To enhance the signal-to-noise ratio for Sample A and B, two pieces of wafers are stacked together for the measurement, enhancing the effective total well thickness. Photomodulated transmission (PMT) technique was also performed in which the transmission modulation created by the chopped external laser excitation produces signals that are derivative of transmission spectra. Details of our absorption and PMT measurements can be found elsewhere [2]. For PL measurements, an Ar laser, a 0.5 m single-path monochrometer, a PbS detector, and a lock-in amplifier were used. The sample temperature was varied from 10 K to RT in a cryostat with a He refrigerator and a heater. The estimated laser excitation level is roughly 1 W/cm^2.

Results and Discussions

Figure 2 shows RT absorption spectra of three samples. Absorption spectra were converted from the transmission data using known QW thicknesses and material parameters. Clear excitonic transitions are observed for e1-hh1 (heavy hole n=1 to electron n=1) transitions in all three samples. Sample A is observed to have double peaks at the absorption edge both in transmission and PMT measurements. This is believed due to vertical (different wells) or lateral (different regions) non-uniformity in quantum confinement energies caused by a monolayer fluctuation in well thickness. Since wells are very thin in Sample A, a small fluctuation in well thickness results in a considerable fluctuation in the confinement energy. The separation between two peaks agree well with the calculated value for the confinement energy difference in wells whose thicknesses differ by a monolayer. Figure 3 shows PMT and absorption spectra for Sample C with assignments for observed peaks. Five transitions including parity-forbidden e1-hh2 and e2-hh1 transitions are observed. Transition energies were determined based on PMT measurements, which, due to their derivative-like signals, can be more accurate [3]. Transition energies were also calculated by solving the energy levels of electrons and holes in finite-barrier QWs. The values of band-offsets between wells and barriers were determined from the model solid theory [4]. For simplicity, the bulk electron and hole effective mass values with energy-dependent non-parabolicity correction for electrons were used. Corrections due to the strain nor the built-in electric field was not considered. With this relatively simple model, the calculated values agree well with the experimentally determined values for the ground state transitions, but the agreement is not as good for the excited states. This is probably due to uncertainties in the values of effective masses and/or band-offsets that were used for the calculations. From the separations of e1-hh1 and e1-lh1 peaks (for Sample A with double peaks, the more dominant peak at the higher energy was taken as the e1-hh1 peak for this estimation), the values of heavy and light hole splitting are estimated to be 75 meV, 78 meV and 79 meV for Sample A, B and C, respectively. Compared to these, 7.2 nm wide lattice-matched InGaAs/InAlAs multiple QWs characterized in the same manner have the splitting of only 39 meV.

Sample	L_z (nm)	S (eV/cm)	E_b (meV)	λ_{ex} (nm)	μ (m_o)
A	2.5	406	7.8	13.1	0.038
B	5.0	240	7.3	13.8	0.038
C	7.5	116	5.8	17.2	0.031
LM QW	7.2	213	8.0	12.2	0.046

Table 1: Estimated Exciton Parameters

To estimate the exciton parameters, integrated intensities of excitonic absorption are first estimated from the areas of Gaussian curves fitted to the lower energy sides of e1-hh1 transitions in the absorption spectra, as shown in Figure 2. Two separate Gaussian curves are used for Sample A. Using the expression for the integrated intensity, S, as given in [5], the value of exciton radius, λ_{ex}, can be determined. Furthermore, solving in a variational manner the equation for exciton binding energy, E_b, as a function of exciton radius [6], E_b and in-plane reduced effective mass, μ, can be estimated. Table 1 lists all the estimated values for three strained multiple QW samples as well as for a reference lattice-matched InGaAs/InAlAs multiple QW sample characterized in the same manner. It is clear that e1-hh1 excitons in compressively strained QWs have lower binding energies and larger radii than those in lattice-matched QWs. This is due to the reduction in the value of in-plane reduced effective mass caused by the compositional change as well as compressive strain. With the same well composition, the narrower wells have excitons of larger exciton binding energies and smaller radii, as expected from the enhanced exciton confinement.

While RT absorption is dominated by the free excitonic effect, it is not the case for RT luminescence. Figure 4 shows PL and absorption spectra of three samples together. The amplitudes of peaks in the figure are scaled in different amounts for an easier comparison. For Sample B and C, the PL peaks are at slightly higher energies than absorption peaks. The separations between PL and absorption peaks (about 7 meV for B, and 5 meV for C) are close to the exciton binding energies estimated above. This indicates that RT luminescence is dominated by band-to-band rather than excitonic recombination. More quantitative analysis will require a detailed line-shape fitting that includes both excitonic and band-to-band recombinations [7]. In the case of Sample A, a careful examination reveals there are three peaks, two of which have slightly higher

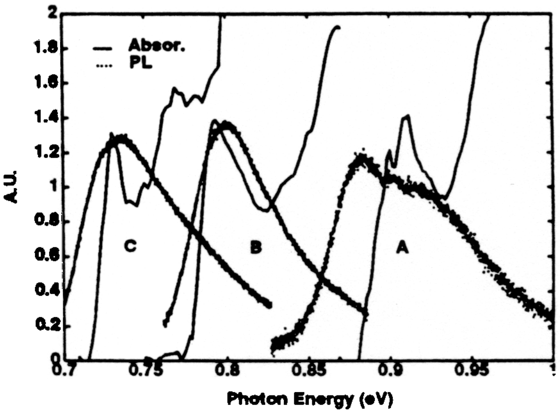

Figure 4: Absorption vs. PL

energies than corresponding absorption peaks. This can be again explained by non-uniformity in quantum confinement energies. Although PL would favor the peak at the lowest energy, it is presently not clear why absorption spectrum does not show any trace of this peak.

PL measurements were done at various temperatures ranging from 10 K to RT so that luminescence characteristics can be investigated as a function of temperature. Figure 5 shows the PL peak positions for different cryostat temperatures. Data for Sample B and C are vertically shifted for an easier comparison. Interestingly, all three samples show different temperature dependence. For Sample C, two clearly resolvable peaks are observed up to 190 K. At low temperature, the low energy peak is dominant but as temperature increases the high energy peak becomes more dominant, and at around 210 K the lower energy peak gets completely buried in the high energy peak. The separation between these two peaks is about 7.5 meV at low temperature but decreases to 5.5 meV at around 100 K. These observations can be explained by assigning the high energy peak to band-to-band and the lower energy peak to excitonic transition. The separation of 5.5 meV is comparable to the exciton binding energy estimated

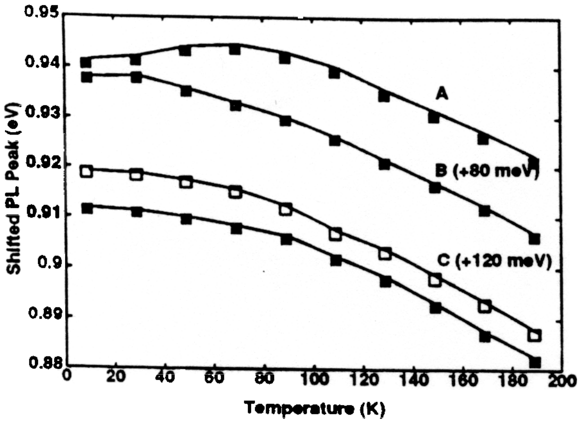

Figure 5: PL Peaks vs. Temperature

earlier. At low temperature, the binding energy is larger because excitons are trapped by impurities or interface defects [8]. Band-to-band recombination can be observed even at very low temperature probably because the exciton binding energy in Sample C is very small. Similar observation has been made in GaAs QWs [9]. For Sample B, only one clearly resolvable peak is observed throughout the entire temperature range. Although it is very probable that luminescence at low temperature is due to bounded excitons, it cannot be confirmed by PL data alone. It should be noted, however, that at around 100 K a shoulder develops in the higher energy side of the dominant peak that eventually becomes the dominant peak above 200 K. Again, this is interpreted as the shifting from excitonic to band-to-band transition for the dominant recombination process at high temperature. Sample A shows pronounced bounded-exciton effects at low temperature. The increase in exciton binding energy is estimated to be about 8 meV by projecting the free exciton peak position from the high temperature values with the calculated bandgap dependence on temperature. Compared to 2 meV estimated for Sample C, this larger increase is expected from the narrow well thickness in Sample A. Although the exact nature of these bounded excitons will require more detailed studies, this clearly demonstrates that binding energies of bounded excitons depend on the well thickness. From the above observations, the dominant recombination process for the samples under present study is determined to be due to bounded excitons for temperature below 100 K, and, at least for Sample B and C, free excitons between 100 to 200 K and band-to-band transitions above 200 K.

Summary and Acknowledgment

We have investigated the excitonic transitions in InGaAs compressively strained QWs by absorption and PL. From the analysis of absorption spectra, quantitative exciton parameters were estimated as a function of well thickness. From PL, it was shown that the luminescence characteristics are greatly influenced by well thickness as well as temperature. One of the authors (W.-Y. Choi) would like to thank Dr. Emil Koteles formerly at GTE and Dr. Paul Gavliovich at Polaroid for many helpful discussions. This work was supported by Joint Services Electronics Program through the MIT Research Laboratory of Electronics, Contract No. DAAL03-92-0001, and by DARPA through the National Center for Integrated Photonics Technology, USC Subcontract No. 542383.

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